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V. Wysochin, PhD, Assoc. Prof.,
V. Nikulshin, DSc., Prof.,
A. Denysova, DSc., Prof.
Odessa Polytechnic National University, 1 Shevchenko Ave., Odesa, Ukraine, 65044; e-mail: vvwin.od@gmail.com

INFLUENCE OF A TWO-STAGE HEAT RECOVERY SCHEME ON THE OPERATION OF THE PV-MD COLLECTOR

В. Височин, В. Нікульшин, А. Денисова. **Вплив схеми двоступінчатої рекуперації теплоти на роботу PV-MD колектора.** Ефективність виробництва електроенергії сонячним модулем істотно визначається термічним режимом роботи. Одним із прогресивних способів впливу на термічний режим є випарне охолодження, що при дистиляції солеутримуючих вод дає можливість управляти температурою сонячного елемента й одержувати вторинний продукт у вигляді прісної води. При каскадній багатоступінчастій рекуперації теплоти випару вибір схемного рішення технологічного процесу охолодження дозволяє оптимізувати сполучення електричної й дистиляційної продуктивності фотомодуля. У роботі проведений аналіз формування температурного поля абсорбера гібридного сонячного колектора (PV-MD), охолоджуваного при двоступінчастій дистиляції сольового розчину з рекуперацією теплоти пари. Метод аналізу дозволяє досліджувати характеристики PV-MD-колектора - температури абсорбера й теплоносіїв, продуктивність системи по електроенергії й дистиляту при реалізації протиточної і прямоточної схем руху розчину, а також у залежності від умов роботи модуля. Ціль роботи - синтез методу розрахунку експлуатаційних характеристик гібридного сонячного колектора з дистилятором при каскадному способі тепломасообміна теплоносіїв і виявлення раціональної технологічної схеми пристрою. Математична модель гібридного сонячного колектора характеризується можливістю локального аналізу процесів тепломасообміна для реальних умов сонячної й кліматичної ситуації. Аналіз тепломасообміну у варіантних умовах показав, що вибір схеми руху теплоносіїв практично не залежить от умов виробництва електроенергії, але істотно визначається впливом спрямованістю потоків теплоносіїв на процес дистиляції. За умовами раціоналізації процесу дистиляції для досягнення найбільшого рівня виробництва дистиляту ефективної є схема прямоточного каскадного руху розчину.

Ключові слова: гібридний сонячний колектор, метод PV-MD, температурний режим, виробництво дистиляту, виробництво електроенергії

V. Wysochin, V. Nikulshin, A. Denysova. **Influence of a two-stage heat recovery scheme on the operation of the PV-MD collector.** Production efficiency of the electric power the solar module is essentially defined by a thermal operating mode. One of progressive ways of affecting on a thermal regime is vapour cooling which at distillation of saliferous waters gives the chance to operate temperature of the solar cell and to gain a by-product in the form of sweet water. At cascade multistage recovery evaporation heats sampling of the circuit solution of a process of cooling allows to optimise a combination of electric and distillation productivity of the photomodule. The analysis of formation of temperature pattern of an absorber of a hybrid solar collecting channel (PV-MD), a salt solution chilled at two-level distillation with recovery warmth of steam is in-process carried out. The analysis method allows to investigate PV-MD-collecting channel characteristics - temperatures of an absorber and heat-transfer agent, productivity of system on the electric power and distillate at implementation of counter flow and direct-flow circuit designs of traffic of a solution, and also depending on module working conditions. The work purpose - synthesis of a method of calculation of opeating characteristics of a hybrid solar collecting channel with the finestiller at the cascade way Heat and mass transfer heat-transfer agent and revealing of the rational technological circuit design of the device. The mathematical model of a hybrid solar collecting channel is characterised by possibility of the local analysis of processes Heat and mass transfer for real conditions of a solar and climatic situation. The analysis Heat and mass transfer in alternative conditions showed that sampling of the circuit design of traffic of heat-transfer agent practically does not depend on electric power conditions of production, but is essentially defined by agency of directions of streams of heat-transfer agent on distillation process. On conditions of rationalisation of process of distillation for achievement of the greatest level of production of distillate the circuit design of direct-flow cascade traffic of a solution is effective.

Keywords: hybrid solar collector, method PV-MD, temperature regime, distillate production, electricity production

Introduction

The degree of heating of the photomodule has an effect on the efficiency of electric energy production [1, 2, 3]. Lowering the heating temperature of the device is achieved by various methods. The progress of the development of photo modules has led to the spread of active methods of cooling modules. These methods allow you to adjust the temperature of the device and utilize the cooling heat, which increases the overall energy efficiency of the device [1 – 5]. In the PVT hybrid collector, the photovoltaic elements are cooled using a coolant pumped through the channels in the rear part of the module [2 – 5]. The disadvantage of such devices is complications with the use of cooling heat, which is characterized by a low temperature potential. In a PV-MD hybrid module, the heat removed from

the absorber is used to evaporate water from the salt solution, which is a cooling coolant [1, 6, 7]. The improvement of the method occurred when using multistage membrane distillation (MSMD), which improves the efficiency of water distillation in the PV-MD module due to the regeneration of the latent heat of condensation of steam for heating water on the connected stages of the device [6, 7]. The use of a heat exchange device leads to the formation of characteristic temperature fields, the change in the configuration of which allows optimizing the processes that determine the productivity of distilled water and electricity in the module.

Analysis of recent research and publications

Three-stage energy recovery in the MSMD device is proposed in [6]. Each stage is carried out in four separate layers: a thermally conductive layer, a hydrophilic porous vaporization layer, a hydrophobic porous MD membrane layer for vapor penetration, and a water vapor condensation layer. Heat is transferred through the heat-conducting layer to the main hydrophilic porous layer. The incoming solution in the hydrophilic porous layer is heated to the formation of water vapor, which passes through the hydrophobic layer of the porous partition and condenses in the condensation layer in the form of pure water.

The vapor pressure difference caused by the temperature gradient between the vaporization and condensation layers is the driving force for vaporization and vapor condensation. The latent heat of water vapor released during condensation at each stage is used as a heat source for vaporization at the next stage [6]. Thus, the design allows reuse of vaporization heat, increasing the productivity of the distillation process relative to a single cycle.

Experimental studies of the model of the three-stage device in [6] showed that the temperature level of the heat-conducting layers is a sufficient potential of the heat-mass transfer process. The research was carried out with the scheme of movement of the rising solution, that is, the countercurrent scheme with respect to the heating element - the absorber. The research was conducted on a model that had a size significantly different from real devices. The factors of modeling and optimization of the motion scheme were not discussed in [6]. Therefore, additional studies are needed to use the MSMD method on devices of common sizes.

The most informative method of studying the thermal modes of operation of collectors is the one carried out on analytical models. Obtaining the necessary information directly depends on the completeness and adequacy of the mathematical description. A mathematical model that meets the requirements of the given task is proposed in [1].

The purpose of the work

Synthesis of the method for calculating the operational characteristics of the PV-MD hybrid solar collector with a distiller in the cascade method of heat and mass exchange between the solution and the distillate. Identification of a rational technological scheme of the device for real operating conditions caused by internal and external influences.

Modeling and results of physical analysis

For the analysis, a two-stage scheme was chosen, which allows to identify the directions of development of the structure and its operational capabilities. For a two-stage scheme, there are possible mode options, which are shown in Fig. 1. According to the scheme (Fig. 1, *a*), the solution enters the hydrophilic porous layer of the second stage, is heated through a separating wall from the distillate condensate, and after partial evaporation is passed to the first stage, in which it also undergoes the stage of heating during interaction with the absorber and evaporation in the hydrophobic layer of the porous partition . This scheme corresponds to schemes [1, 6] in terms of flow directions, so let's call it basic. According to scheme (Fig. 1, *b*), which is a modification of the basic one, the solution enters the hydrophilic porous layer of the first stage, heats up when interacting with the absorber and, after evaporation, passes to the second stage, in which it is heated through a separating wall from the distillate condensate and, after partial evaporation, is removed from the module.

The target indicator that characterizes a photocell is electric power, which depends on the density of the solar radiation flow, the ambient temperature, and the temperature of the solar energy absorber [8]:

$$P = P_{SC} k_{l.e} \frac{H}{H_{SC}} [1 + \alpha_p (t_{ab} - t_{SC})] ,$$

where P_{SC} – nominal capacity of the battery under standard conditions (SU);

H — radiation flux density;

H_{SC} — solar radiation flux density under standard conditions;

$k_{l.e}$ — coefficient of reduction of battery efficiency, taken as – $k_{l.e}$ =0.95;

t_{SC} — absorber temperature;

t_{ab} — absorber temperature under standard conditions;

α_P — temperature coefficient of electric power, K^{-1}.

The standard conditions are determined at the solar radiation flux density $H_{SC} = 1$ kW/m^2 and the absorber temperature at the STC standard $t_{SC} = 25$ °C.
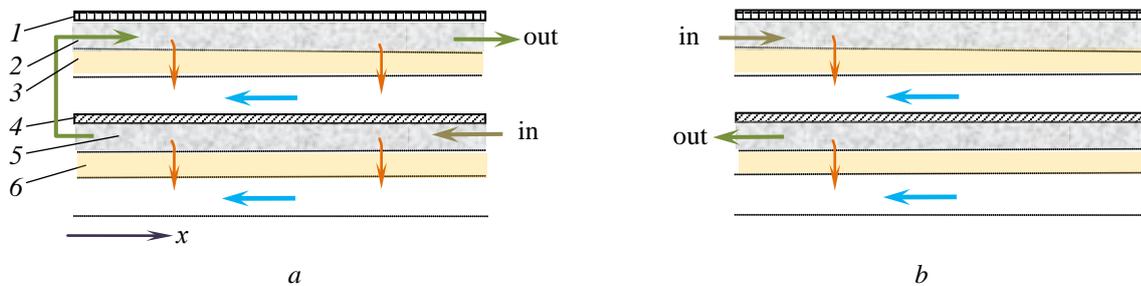
Fig. 1. Mode diagrams of the cooling device of the collector, basic (*a*), its modification (*b*): *1* – absorber; *2* – hydrophilic porous layer of the 1st stage; *3* – hydrophobic layer of the porous partition; *4* – capacitor; *5* – heat-conducting wall; *6* – hydrophilic porous layer of the 2nd stage. Arrows show the directions of flow of solution (green), distillate (blue) and steam (yellow)

The thermal balance of the collector is formed under the influence of external and internal conditions, the first of which are the intensity of radiation of the absorber and heat exchange with the environment, the second are formed during the reproduction of processes: heat exchange between the absorber and the salt solution, evaporation of water from the solution and condensation of steam in the condenser, as well as when heat exchange between the distillate (condensate) and the solution through the separating heat-conducting wall. The identified processes are described by a system of energy conservation equations with respect to local characteristics, which takes into account model representations [9].

For the absorber:

$$H(\tau\alpha)(1-\eta_{ph}) - h_{abs-a}(t_{abs}-t_a) - h_{abs-s}(t_{abs}-t_s') = 0,$$

where H – intensity of solar radiation;

$(\tau\alpha)$ – optical characteristics of the collector;

η_{ph} – efficiency of conversion of solar energy by the collector;

h – heat transfer coefficient; t –temperature.

For the solution in the first step:

$$h_{abs-s}(t_{ph}-t_s') - (cg)_s' \frac{dt_s'}{dx} - g_d'r = 0,$$

where c – heat capacity;

g – flow rate;

r – heat of vaporization.

For the distillate in the first stage condenser:

$$U_{d-s}'(t_d'-t_d'') - (cg)_d' \frac{dt_d'}{dx} - g_d'r = 0,$$

where U – heat transfer coefficient.

For the distillate in the second-stage condenser:

$$(cg)_d'' \frac{dt_d''}{dx} - g_d''r = 0.$$

For the heater and evaporation of the solution in the second stage:

$$U_{d-s}(t'_d - t''_s) - (cg)_s \frac{dt''_s}{dx} - g''_d r = 0 .$$

Here the accepted indices are:
– *abs* – absorber; *s* – solution;
– *d* – distillate; one stroke – the first degree, two strokes – the second degree.

The value of the efficiency of the photocell η_{hp} depends on the temperature, and in the region of positive temperatures can be represented by the dependence [8]:

$$\eta_{hp} = \eta_{maxSC}[1 + \alpha_P(t_{abs} - t_{SC})],$$

where η_{maxSC} is the efficiency of the photocell at the point of maximum power under standard conditions.

The system of equations is supplemented with boundary conditions characteristic for the operation of solar devices [8]. Boundary conditions are specified by the dependence obtained during data processing [6] from the determination of distillate productivity when implementing the MSMD method, kg/(m²h):

$$g_d = 0.0223 \cdot t_s - 0.229.$$

The input flow rate of the solution is taken to be equal to 4.2 kg/(m²h) [6]. The characteristic size of the module was determined by its length, which was assumed to be equal to 1.7 m. The boundary conditions were chosen for the terrain with a latitude of 46° for different seasons.
The system of equations was solved by the numerical method. Based on the results of solving the system of equations, the local temperatures of the absorber, solution, and distillate, as well as the distillate consumption, were determined. Taking into account the fact that the temperature change in the system occurs along the flow of coolants, the normalization of the considered indicators with respect to the width of the module was applied.

The nature of the temperature change of the solution along the flow in the first and second stages, of the distillate in the first stage for both mode schemes is shown in Fig. 2. In the first stage, the temperature graphs of the solution t'_s are uneven in both regimes – the temperature increases along the flow (the flow directions here are the same). However, in mode (*a*), the rate of temperature change is higher, which is due to a decrease in the value of the heat equivalent (the product of the heat capacity consumption) due to the evaporation of the solution at the previous stage (the second from the absorber, but the initial downstream). Accordingly, the temperature level of the solution at the entrance to the 1st stage in mode (*a*) is lower than in (*b*). However, at the end of the stage, the temperatures converge, as a result of the influence of the heat capacity of the absorber, which has a predominant weight in the thermal balance of the system.
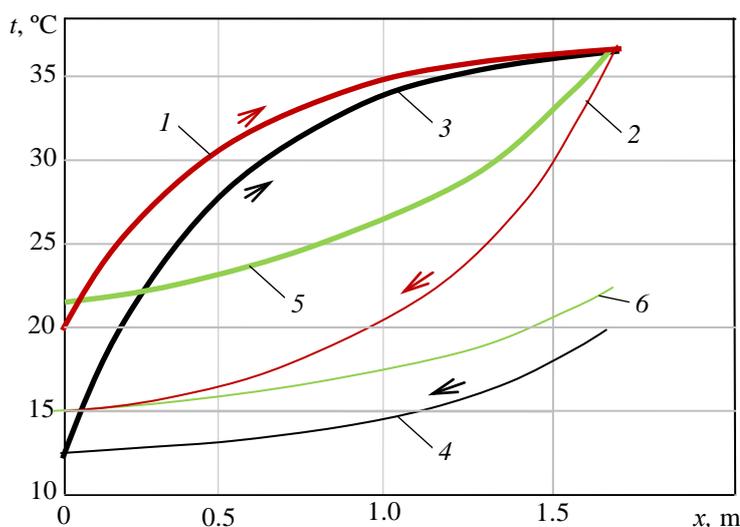
Fig. 2. Longitudinal fields of temperatures in the flow of the solution in steps according to the diagrams (Fig. 1), respectively, (*b*): *1* – the first; *2* – second; (*a*): *3* – the first; *4* – second; in the distillate stream in the first stage according to schemes: *5* – (*b*); *6* – (*a*). Arrows indicate the directions of movement of the coolant
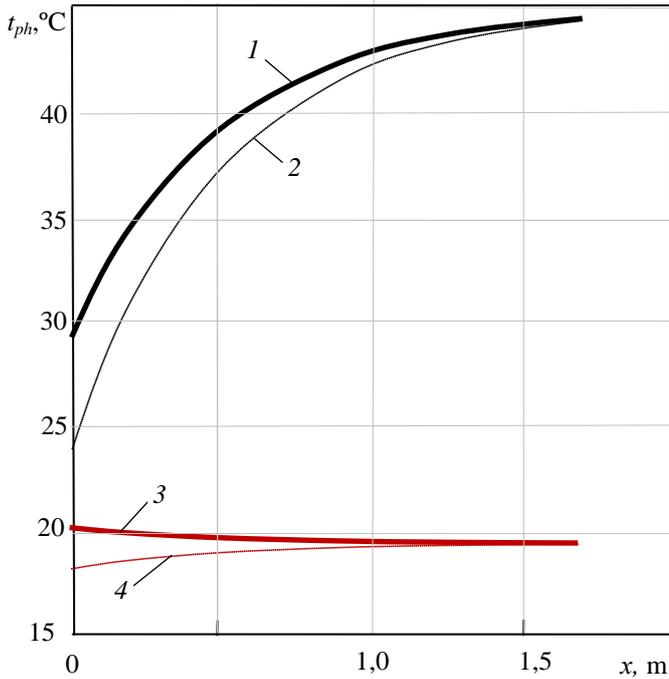
Fig. 3. Temperature change of the absorber along the panel in summer in modes, according to the diagrams (Fig. 1): *1* – (*b*) 2 – (*a*); and in winter *3* – (*b*); *4* – (*a*)

In the second stage, the temperature t_s'' of the solution in both modifications decreases along the flow (the direction of the flows here is the same), but at a different rate; in regime (*b*), the rate of temperature change is greater, which is associated with the difference in the heat equivalents of the flows. In general, the temperature level of the solution in the second stage in mode (*b*) is higher, which should facilitate distillation.

The temperature of the distillate t_d' in the first stage in mode (*b*) differs by a higher level, because it is formed under the influence of two streams of solution - in the first and in the second stage, which have a significant temperature potential for this mode. The temperatures of the distillate and solution in mode (*b*) indicate an increased intensity of the distillation process, while the temperature levels of the solution in the first stage, which form the temperature field in the absorber, differ little in both modes.

The temperature of the absorbers, according to the solution heating schedule in the first stage, increases along the panel – along the flow (Fig. 3). At the same time, at the beginning of the panel, the temperature of the absorber in mode (*b*) is higher than in (*a*). In summer, the difference reaches 33%. At the end of the panels in both modes, the temperatures become almost equal. In winter, the local heating of the panels is mostly uniform, with a slight difference in the initial area.

It should be noted that the temperature graphs for the surface of absorbers without a forced cooling system are significantly higher than the level of cooled panels by more than 3 times.

The degree of heating of the photo-panel is expressed in the production of electricity. The temperature level of the panel is the result of the influence of several factors – external and internal. External factors – ambient temperature and radiation level are formed depending on seasonality. They mainly affect the production of electricity. At the same time, the irradiance factor is decisive, because the air temperature during the transition from the summer level to the winter level does not give a sufficient increase in productivity to compensate for the decrease in electricity generation at low irradiance.

In addition to the dependence on the season, local electricity production in the

Fig. 4. Change in local electricity generation along the panel in summer in modes, according to the diagrams (Fig. 1): *1* – (*a*); *2* – (*b*);in winter: *3* – (*a*); *4* – (*b*)

panel is characterized by spatial unevenness, which is due to the influence of an internal factor – the temperature field of the absorber, the type of which depends on the heat exchange in the module system. The influence of temperature is manifested both in the level of electricity production and in the rate of change of productivity along the panel (Fig. 4). In general, productivity and the rate of its decrease in mode (*b*) are less than in (*a*). However, the difference in average electricity production in summer is only (1.2...2.0) percent. In winter, this difference is even smaller. This circumstance gives reason to exclude, as a determining factor, the influence of the scheme on the level of electricity production

Against the background of a slight decrease in electricity production when switching from one scheme modification to another, distillate production in mode (*b*) is significantly higher than in (*a*) (Fig. 5). The analysis shows that this is typical for both stages of this scheme. True, in the first stage at the end of the panel, due to the equality of solution temperatures, the performance in both modifications becomes equal.

Fig. 5. Changes in the local intensity of distillation along the modules in the summer according to the regimes in the 1-st step, according to the diagrams (Fig. 1): *1 – (b)*; *2 – (a)*, and 2 stages: *3 – (b)*; *4 – (a)*

In the second stage, the distillate productivity in modification (*b*) is higher along the entire panel, and there is a tendency for this parameter to grow along the panel. At this stage, the difference in the production of distillate is manifested to the greatest extent – up to 2 times.

The total production of distillate for the summer period is as follows: mode (*a*): in the first stage $3.5 \cdot 10^{-3}$ kg/(m·s), in the second stage $0.61 \cdot 10^{-3}$ kg/(m·s), total – $4.11 \cdot 10^{-3}$ kg/(m·s); mode (*b*) – in the first stage $3.8 \cdot 10^{-3}$, in the second stage $1.46 \cdot 10^{-3}$ kg/(m·s), total – $5.26 \cdot 10^{-3}$ kg/(m·s); Thus, distillate production in mode (b) for the summer period is 28% higher.

In winter, the total production of distillate is less. Mode (*a*): 1st degree – $3.33 \cdot 10^{-4}$ kg/(m·s), 2nd degree – $4.5 \cdot 10^{-4}$ kg/(m·s), sum – $7.83 \cdot 10^{-4}$ kg/(m·s). Mode (*b*): 1st degree – $6.68 \cdot 10^{-4}$ kg/(m·s), 2nd degree – $3.4 \cdot 10^{-4}$ kg/(m·s), sum – $1.01 \cdot 10^{-3}$ kg/(m·s). The difference is 29% in favor of mode (*b*).

The difference between the summer period and the winter period is about 4 times, which is related to the low temperature of the absorber. This circumstance indicates that the production of distillate is more justified in the summer period. It should be noted that electricity generation also decreases in winter.

Conclusions

Analytical studies of the influence of the operational energy-technical characteristics of the PV-MD hybrid solar collector in the conditions of two-stage recuperative heat and mass transfer of salt solution and distillate were carried out in order to identify a rational flow pattern.

According to the results of the study, it is shown:

The temperature level of the solution in both stages in mode (*a*) is lower than in (*b*), which indicates the possibility of intensifying the distillation process by changing the flow pattern.

The temperature graphs for the surface of the absorber without a forced cooling system are significantly higher than the level of the cooled panels by more than 3 times. However, the temperature of the absorber in the cooled mode is uneven along the panel and differs for the considered schemes. In mode (*b*) at the beginning of the panel, other things being equal, it is higher than in mode (*a*), in the summer period the difference is the largest, reaching 33%. At the end of the panels in both modes, the temperatures become almost equal.
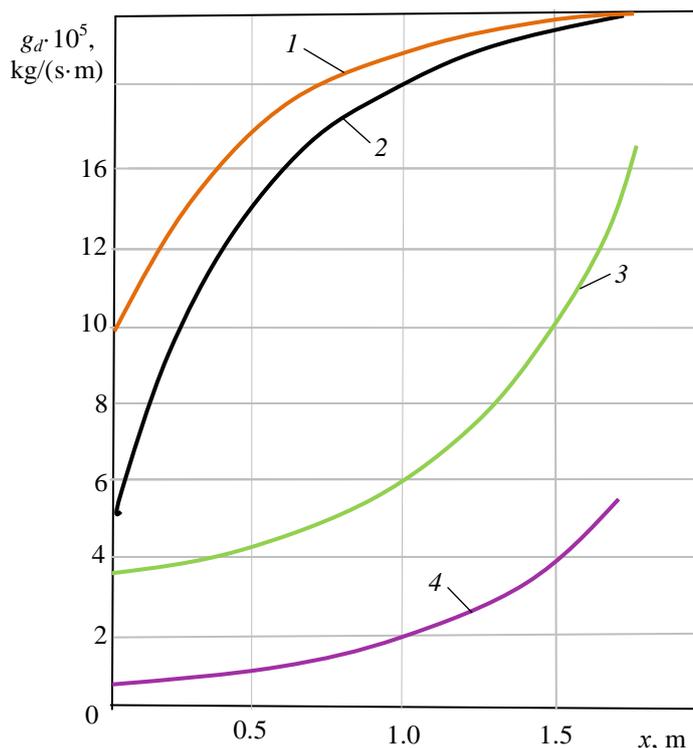
The production of electricity, according to the level of heating of the absorber, in mode (*b*) is less than in (*a*). However, the difference in the average electricity production in summer is only 1.2...2.0 percent, in winter the difference is even less. A small difference in this indicator by options gives reason not to take into account when rationalizing the design, as a determining factor for electricity production, the influencing factor of the scheme.

Distillate production in mode (*b*) for both stages is significantly higher than in the alternative option. In the second stage, the difference in the production of distillate is manifested to the greatest extent – up to 2 times. A significant dependence of distillate productivity on the season (which reaches 4 times) indicates that the production of this secondary product is more justified in the summer period. Thus, the analysis of the considered flow patterns in the cooling device shows a significant advantage of option (*b*).

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Височин Віктор Васильович; Victor Wysochin, ORCID: http://orcid.org/0000-0003-2279-203X
Нікульшин Володимир Русланович; Vladimir Nikulshin, ORCID: http://orcid.org/0000-0001-5946-8562
Денисова Алла Євсіївна; Alla Denysova, ORCID: http://orcid.org/0000-0002-3906-3960